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## Abstract

As a part of CFD code validation efforts within the Icing Branch of NASA Glenn Research Center, computations were performed for natural laminar flow (NLF) airfoil, NLF-0414, with 6 and 22.5 minute ice accretions. Both 3-D ice castings and 2-D machine-generated ice shapes were used in wind tunnel tests to study the effects of natural ice as well as simulated ice. They were mounted in the test section of the Low Turbulence Pressure Tunnel (LTPT) at NASA Langley that the 2-dimensionality of the flow can be maintained. Aerodynamic properties predicted by computations were compared to data obtained through the experiment by the authors at the LTPT. Computations were performed only in 2-D and in the case of 3-D ice, the digitized ice shape obtained at one spanwise location was used. The comparisons were mainly concentrated on the lift characteristics over Reynolds numbers ranging from 3 to 10 million and Mach numbers ranging from 0.12 to 0.29. WIND code computations indicated that the predicted stall angles were in agreement with experiment within one or two degrees. The maximum lift values obtained by computations were in good agreement with those of the experiment for the 6 minute ice shapes and the 22.5 minute 3-D ice, but were somewhat lower in the case of the 22.5 minute 2-D ice. In general, the Reynolds number variation did not cause much change in the lift values while the variation of Mach number showed more change in the lift. The Spalart-Allmaras (S-A) turbulence model was the best performing model for the airfoil with the 22.5 minute ice and the Shear Stress Turbulence (SST) turbulence model was the best for the airfoil with the 6 minute ice and also for the clean airfoil. The pressure distribution on the surface of the iced airfoil showed good agreement for the 6 minute ice. However, relatively poor agreement of the pressure distribution on the upper surface aft of the leading edge horn for the 22.5 minute ice suggests that improvements are needed in the grid or turbulence models.

## Nomenclature

LTPT Low Turbulence Pressure Tunnel (NASA Langley)

MVD	Median Volume Diameter (in $\mu m$ )
LWC	Liquid Water Content (in $g/m^3$ )
IRT	Icing Research Tunnel (at NASA Glenn)
AOA	Angle-of-Attack
S-A	Spalart-Allmaras Turbulence Model
SST	Shear Stress Transport Turbulence Model
$C_p$	Pressure coefficient
$C_{l_{max}}$	Maximum 2D lift coefficient
$\alpha_{C_{l_{max}}}$	Angle where maximum lift occurs

## Introduction

NLF airfoils were designed to achieve lower cruise drag coefficients while retaining the high maximum lift coefficients intended for use in general aviation. Experimental work<sup>[1]</sup> using a clean wing was performed at the NASA Langley LTPT tunnel in the 1980s but the aerodynamic measurement of icing effects has not been performed for this type of airfoil even though a minor ice accretion on such a wing could result in a significant penalty in the aerodynamic performance. In the aerodynamic measurement of iced airfoils and wings performed in the past, many researchers have used ice models with either very smooth surfaces, ones with sand grain roughness or bead type protrusions to simulate the real iced surface. These shapes were assumed to provide performance degradation reasonably close to real ice but the actual difference has not been verified.

The primary purpose of this research was to evaluate the performance of the CFD code against the experimental data. An additional purpose of the test and computation was to investigate the effects of Reynolds numbers as well as Mach numbers on the performance of the iced airfoil. In order to perform this study, actual cast ice made from molds of ice formed in the Icing Research Tunnel (IRT) at NASA Glenn as well as machine generated two-dimensional projections of the ice shapes obtained at one spanwise location were used to investigate the effects of smoothing on the aerodynamic

characteristics. Comparisons were also made for the lift characteristics including the maximum lift and stall angles which are very important factors for safe operations of aircraft.

### **Approach**

The ice shapes used in this study were accreted on the NLF-0414 airfoil in the IRT under the following icing conditions. Icing spray conditions which produced the ice shapes were a median volume diameter (MVD) of  $20\mu m$ , a static air temperature of  $-5^{\circ}C$ , a model attitude of  $2^{\circ}$ , a liquid water content (LWC) of  $0.54 g/m^3$  and 6 and 22.5 minute spray times. Castings were made of these ice shapes for the LTPT aerodynamic test. The Mach number was 0.21 and Reynolds number was 4.6 million based on the chord. The numerical grid sensitivity analysis explained later in this study was based on this experimental condition.

### Wind Tunnel Test<sup>[2]</sup>

The NLF-0414 model tested in the LTPT had a chord of 36 inches and a span of 36 inches. It had a removable leading edge in order to attach different ice shapes. Figure 1 shows the three-dimensional cast ice pieces mounted with a stainless steel piece for pressure taps sandwiched between them. Figure 2 shows a similar mounting of the machine-generated two-dimensional model. Inside the test section of the LTPT, side wall boundary layer control was used to ensure the two-dimensionality of the flow. The experimental lift data was obtained at all angles including the post-stall angles but due to the enormous time requirements to operate the wake survey, drag data was obtained only at limited number of angles for most cases. Both force balance and integration of surface pressure data were used for the calculations of global force characteristics. Due to its accuracy, the surface pressure was used to obtain the overall lift and the force balance data showed good agreement with it. Full experimental results can be found in reference 2. Low speed wind tunnel wall and blockage corrections<sup>[3]</sup> were applied to the experimental data and these were compared to computational results run under external flow conditions. Advantages of LTPT were wider range of Reynolds and Mach numbers and low turbulence level than ones available in smaller atmospheric tunnels. The test Reynolds numbers were ranged from 3 to 10 million and the Mach numbers were ranged from 0.21 to 0.29.

### Surface Modeling

Past research efforts showed that proper modeling of the iced surface and a grid sensitivity study are essential for the accurate prediction of aerodynamic properties<sup>[4]</sup>. When the sur-

face of the 3-D ice castings was modelled for 2-D computations, the digitized ice shape at one spanwise location was used. Only the areas which made grid generation almost impossible were treated to have smoother geometry fit for grid generation. Surface modeling tool kit 'Smag-Ice<sup>[5]</sup>' developed in-house at NASA Glenn was used for the treatment of such areas and to construct smoothed geometry for the fabrication of two-dimensional ice shapes by Stereo-lithography machine. The same approach reported in references 4 was used to model the iced surfaces by using 20% level of control points for the 22.5 minute ice and 50% for the 6 minute ice<sup>[2]</sup>.

### Grid Generation

The modeling of complicated 3-D surfaces is still technically very challenging and the computation of such cases would be very expensive. Although the ice castings represent truly three-dimensional surfaces, all grids for this study were generated for 2-D computations. Figures 3a and 3b compare the original digitized ice shape and the smoothed ice shape for the 22.5 minute ice. A similar smoothing was also performed for the 6 minute ice. A series of grids with variable densities both in circumferential and normal directions were first generated to determine the optimum resolution. Figures 4a shows the grid block strategy around the leading edge of the 22.5 minute ice. A C-type grid was used for the inner block with the farfield boundaries placed at a distance of 15 chord lengths from the body surface in all directions. This blocking method was used to ensure good grid quality control for the inner block around the complicated ice shapes. Figure 4b shows grid lines near the leading edge of the smaller 6 minute ice. Elliptic grid generation was performed using the GRIDGEN program.

### Numerical Methods

The WIND code<sup>[6]</sup> capable of simulating complex flow fields was used for the calculation of the current problems. It is capable of multi-zone, 2-D/3-D, implicit/explicit, and steady/unsteady computations with various turbulence models. The governing equations in WIND code are formulated using the finite-volume approach and the specification of the discretization on the right hand side is flexible. The choice includes standard Roe upwind, physical Roe upwind for stretched grids and Coakley upwind. The spatial accuracy can be adjusted to the fifth order if desired by the user. Several turbulence models including the Spalart-Allmaras (S-A)<sup>[7]</sup> and the Baldwin-Barth (B-B)<sup>[8]</sup> one-equation turbulence models and Shear Stress Transport (SST) two-equation turbulence model<sup>[9]</sup> were used for the grid sensitivity test for the determination of the best performance. The SST model

is a hybrid model which blends the solution of the  $k - \omega$  model near a solid surface and the  $k - \epsilon$  model elsewhere including the shear layer. A fully turbulent flow was assumed for the computation considering the roughness of the ice shapes and partly due to lack of ability to include transition effects. At the far field boundary, a non-reflecting type boundary condition was applied.

#### Grid Sensitivity Test

In order to achieve high quality numerical results, a series of grids for the inner block having different densities in both normal and circumferential directions were constructed (the dimension of the outer block was fixed). The WIND code was then run with three different turbulence models described above, using these grids, and the aerodynamic properties were compared to the experiment.

The first set of grids constructed were used for an investigation of the normal direction sensitivity, which was followed by a study of the effect of packing grid points in the circumferential direction. Combination with various turbulence models was also attempted to determine the proper model for each ice shape. In the first study applied to the 22.5 minute 3-D ice, the number of grid points used in the normal direction were 71, 81, 91, and 101 while the circumferential direction grid number was fixed at 491. Figure 5 shows the effect of this normal direction grid packing. It showed that about 101 grid points were needed for good agreement with experimental data. When the number of grid points in normal direction was further increased from 101, it did not result in significant change of lift. Application of the three turbulence models for 491 x 81 inner block grid showed that the Spalart-Allmaras models was the best one for this type of relatively large ice with horns (Figure 6).

Based on this result, the normal direction grid was fixed at 101 points and the circumferential grid densities of 321, 361, 421, 441, 491, and 501 were applied. Figure 7 shows the result with three grid resolutions indicating that the change of grid density in circumferential direction did not affect the lift as much as the normal direction change did. Also in this case, grid points more than 441 did not change the maximum lift value significantly. In all cases, the stall angle was the same regardless of the number of points used. The reasonable resolution of 441x101 was used for the rest of the computation for the 22.5 minute 3-D ice. When the same approach was applied to the 22.5 minute 2-D ice, 401x101 grid was determined to be the best one. In the case of 6 minute ice, the best performing turbulence model was SST model and the grid resolution for the 2-D and 3-D ice were 351 x 81 and 371 x 81 respectively. For all these studies, the non-dimensional first grid spacing in the normal direction

( $y_1$ , or minimum wall spacing) was  $4.0 \times 10^{-6}$  which was determined from numerical experiments. This value resulted in average value of  $y^+$  less than 1.0 for all ice shapes and flow conditions.

### **Discussions of Results**

Total of five different flow conditions were selected for CFD runs for 6 minute 2-D and 3-D ice (table 1) while seven conditions were applied for the 22.5 minute ice (table 2). Out of these flow conditions, Mach number of 0.21 and Reynolds number of 6.4 million was selected as the representative condition for the discussions to follow.

#### 6 minute 3-dimensional cast ice

Figure 8a shows a comparison of lift versus AOA curves between the computation and the experiment for Mach number of 0.21 and Reynolds number of 6.4 million. The maximum lift obtained by experiment was 1.023 and the computational prediction was 1.019, which was a difference of 0.4%. But the computationally predicted stall angle was 8.3 degrees which was one degree lower than that of the experiment. The difference in the maximum lift ranged from 0.4 percent for this condition to as much as 6.5 percent for  $M=0.12$  and  $Re = 6.4$  million. The stall angle remained unchanged at 8.3 degrees for all five flow conditions and the experimental stall angles were all at 9.3 degrees. Relatively good agreement was also observed in the comparison of the  $C_p$  for all the cases. At the same flow condition as Figure 8a, comparisons at the angle of attack of 0.1 degree and 8.3 degrees (Figures 8b and 8c) showed generally good agreement except near the trailing edge. At 8.3 degree AOA, the  $C_p$  by computation showed slight deviation from the experiment on the upper surface. It should be noted that some differences might come from the fact that the experimental pressure is an uncorrected one obtained at 8.0 degrees (pressure coefficients cannot be corrected while the global forces can be) but the computation was performed at the corrected angle of 8.3 degrees for the fair comparison of lift values. Considering this level of agreement of  $C_p$  curves, the computationally predicted separation region on the upper surface and the velocity distribution pictured in Figure 8d is a reasonable representation of the experimental condition though velocity was not measured in the tests. The next two figures 9 and 10 summarize the effect of Reynolds number and Mach number on the lift. The fact that the Reynolds number did not have as much influence as the Mach number was in agreement with experiment but the margin of difference was greater than experiment especially for the Mach number effect. The decrease in  $C_{l_{max}}$  was 7.5% in going from Mach

number of 0.12 to 0.21 and 8.8% when going from 0.12 to 0.29. In comparison, the experiment showed 1.5% and 3.2% changes. This suggests that the physical model in the code may be sensitive to the compressibility effect caused by the increase in Mach number.

#### 6 minute 2-dimensional smooth ice

For the machine-fabricated smooth ice, comparison showed somewhat larger variations than the 6 minute 3-D ice case. At Mach number 0.12, the  $\alpha_{C_{l_{max}}}$  for experiment was 10.3 degrees while the computational result indicated that it was 9.3 degrees. For the flow condition of Mach number of 0.21 and Reynolds number of 6.4 million, the largest difference was observed between the experiment and the computation (Figure 11). The  $\alpha_{C_{l_{max}}}$  for the computation occurred 2 degrees lower and  $C_{l_{max}}$  was 2.1% lower but for all other flow conditions, one degree difference in the  $\alpha_{C_{l_{max}}}$  was observed as in the 3-D case. The overall difference in  $C_{l_{max}}$  for the five conditions increased only slightly compared to the 3-D cast ice case. Similar trend in the influence of Mach number and Reynolds number on the lift was also observed. The  $C_{l_{max}}$  was 9.5% higher for the 2-D ice shape than for the 3-D ice shape as shown in Figure 12a. This is in good agreement with experiment since its margin was 9%.<sup>[2]</sup> Figure 12b compares the  $C_p$  between the 2-D and the 3-D cases and it shows some differences on the upper surface. In general for both 2-D and 3-D cases, computations predicted  $\alpha_{C_{l_{max}}}$  and  $C_{l_{max}}$  somewhat conservatively by producing slightly lower values.

#### 22.5 minute 3-dimensional cast ice

Figures 13a through 13g show lift,  $C_p$ , and flow field characteristics for the larger 22.5 minute 3-D cast ice under the representative flow condition. In this case, computationally predicted  $\alpha_{C_{l_{max}}}$  was one degree higher at 6.2 degrees than the experimental result of 5.2 degrees. Computational  $C_{l_{max}}$  was 2.0% lower than that of experiment. Although the lift predicted by the computation showed relatively good agreement with the experiment, the  $C_p$  curves compared at 0.1 degree and 6.2 degree AOAs indicated that the computational prediction did not match the experiment at both angles. Especially at AOA of 6.2 degrees, the computational  $C_p$  showed much faster pressure recovery on the upper surface than the experiment. This would cause differences in the separation bubble size and the velocity distribution in it. Bragg, et al<sup>[10]</sup> performed experiments to determine boundary layer transi-

tion for a NACA 0012 airfoil with simulated icing scale roughness at low Mach numbers and Reynolds numbers ranging from 0.75 to 2.25 million. They showed that the fully developed turbulent profiles were not measured until approximately 40% chord location. Although neither flow conditions nor roughness elements on the surface of the study match those of the current study, it is enough to suggest that a certain level of transition effect should be introduced in the CFD computations. Apart from these pressure distribution differences, the Reynolds number and Mach number variations showed very similar effect as the 6 minute ice cases. Figures 14a and 14b showed that increasing the Reynolds number did not have significant effect on the lift at Mach numbers of 0.12 and 0.21 while Figure 14c showed that the Mach number change had more significant effect. The decrease in  $C_{l_{max}}$  was 9.6% in going from Mach number of 0.12 to 0.21 and 12.3% when going from 0.12 to 0.29. This is a quite a bit of contrast to the experiment which showed only about 0.5% change in the  $C_{l_{max}}$  for the three Mach numbers tested at Reynolds number of 6.4 million.

#### 22.5 minute 2-dimensional smooth ice

For this ice shape, the largest lift differential was observed at a Mach number of 0.21 and Reynolds number of 6.4 million as shown in Figure 15a. The  $\alpha_{C_{l_{max}}}$  by experiment was one degree higher at 7.3 degrees than the computation showing one degree shift of the stall angle compared to the 3-D case. Figure 15b showed similar differences in  $C_p$  as the 3-D case but the pressure difference aft of the upper horn and the lower surface was less than that of the 3-D cast ice case. Figure 16a and 16b indicated that there was 2.8% decrease in the  $C_{l_{max}}$  going from 2-D to 3-D and the  $C_p$  data showed no significant difference. This is the greatest disagreement among the 7 conditions (see table 2) computed but at the lower Mach number of 0.12, better agreement with the experiment was observed as shown in Figures 17 and 18. At Reynolds number of 3.0 million, the  $\alpha_{C_{l_{max}}}$  matched at 7.2 degrees and the computational  $C_{l_{max}}$  was only 0.95% lower than the experiment. At higher Reynolds number of 6.4 million, the stall angle was one degree higher for the experiment (8.2 degrees versus 7.3 degrees) and the computational  $C_{l_{max}}$  was 2.4% lower than the experiment.

#### Effect of 2-D and 3-D ice on the lift

Figures 19 and 20 summarize the effect of 2-D and 3-D ice on the lift. Compared to the computational lift for the clean airfoil, accretion of 3-D ice resulted in 37% drop of lift for 6 minute ice and 50% drop for 22.5 minute ice. Similarly for



the 2-D ice, 31% and 48% drop of lift was observed respectively.

### Concluding Remarks

A parametric computational study was performed to evaluate the ability of WIND code to predict the performance degradation of NLF-0414 wing with realistic 3-D cast ice and 2-D machine-generated ice shapes. Computations were performed in 2-D domain with digitized geometry for the 3-D ice shape and smoothed geometry for the 2-D ice shape for a range of Mach and Reynolds numbers. The WIND code generally predicted conservatively lower lift and the  $\alpha_{C_{l_{max}}}$  were in agreement with the experiment within one or two degrees. The  $C_{l_{max}}$  values were in good agreement for the 6 minute ice shapes and the 22.5 minute 3-D cast ice, but were somewhat lower in the case of 22.5 minute 2-D ice for Mach numbers greater than 0.21. Both computations and experiments indicated that Mach number had more effect on the lift than Reynolds number did although greater change on the lift was observed for computations with the increased Mach number. The Spalart-Allmaras turbulence model was the best model for the 22.5 minute ice and the SST model was the best for the 6 minute ice and the clean airfoil. The pressure distribution on the surface of the iced airfoil showed good agreement for the 6 minute ice but relatively poor agreement on the upper surface aft of the leading edge horn for the 22.5 minute ice.

The following observations should be noted for future studies similar to this one. First, agreement in lift characteristics (or global forces) does not guarantee the agreement in pressure distributions. Second, more comprehensive experimental data including drag, pitching moment, and velocity measurements would be helpful for an accurate assessment of the capabilities of the CFD code. The grid sensitivity study and the selection of the proper turbulence models thus could be performed mainly by comparing the lift values against the experiments limiting the accuracy of such a study. Third, the differences in the pressure distribution on the surface of the airfoil suggest that more investigations are needed in constructing better grids especially in the shear-layer-dominated regions aft of large horns, grid adaptations, and better turbulence models which can effectively account for the existence of boundary layer transition. Fourth, considering the fact that the SST model was the best for the smaller 6 minute ice shape but S-A model was the best for the larger 22.5 minute ice shape, more study is recommended for the determination of the best performing turbulence models for different sizes and shapes of ice. Fifth, further investigation is needed to explain the exact causes for the differences in the global force characteristics and the

pressure distributions between the computations and experiments as shown in the current study.

### Acknowledgments

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Table 1. Flow conditions used for the computations of the 6 minute ice

$Re \times 10^{-6}$	$M = 0.12$	$M = 0.21$	$M = 0.29$
4.6		X	
6.4	X	X	X
10.0		X	

Table 2. Flow conditions used for the computations of the 22.5 minute ice

$Re \times 10^{-6}$	$M = 0.12$	$M = 0.21$	$M = 0.29$
3.0	X		
4.6		X	
6.4	X	X	X
10.0	X	X	



Figure 1 3-D ice castings mounted in the test section



Figure 2 2-D smooth ice mounted in the test section

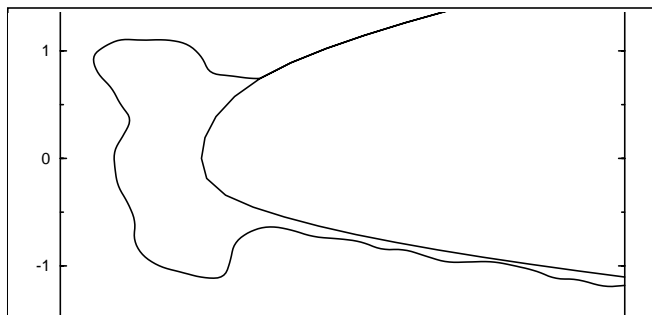
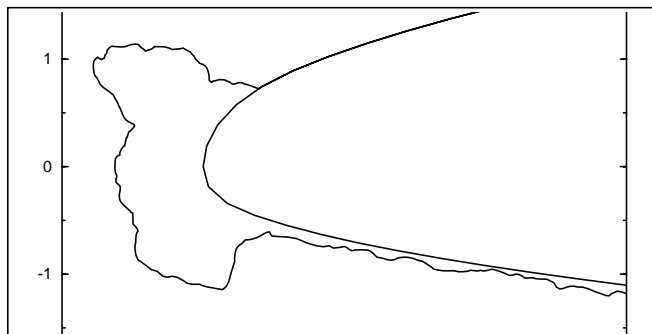


Figure 3a (top) Geometry for the 3-D 22.5 min. ice

Figure 3b (bottom) Geometry for the 2-D 22.5 min. ice

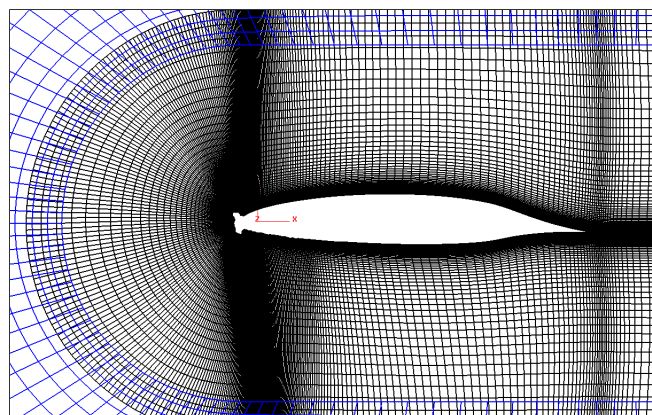


Figure 4a 2-block grid system for the 22.5 minute ice

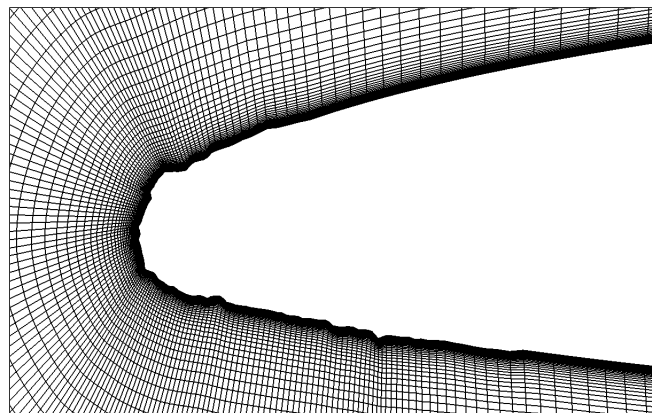


Figure 4b Grid around the leading edge of the 6 min. ice

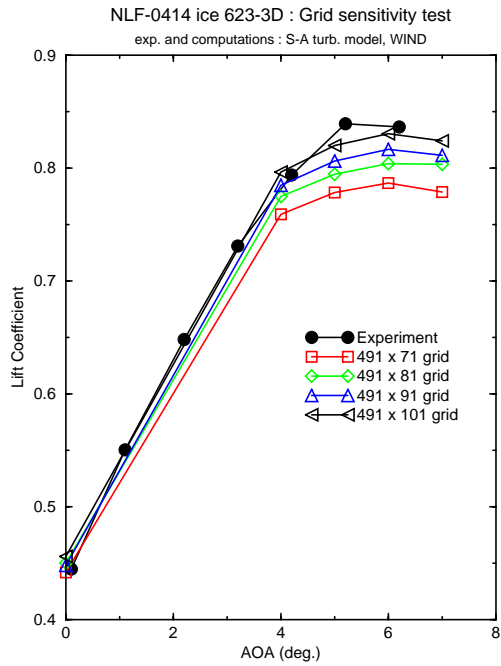


Figure 5 Normal direction grid density study

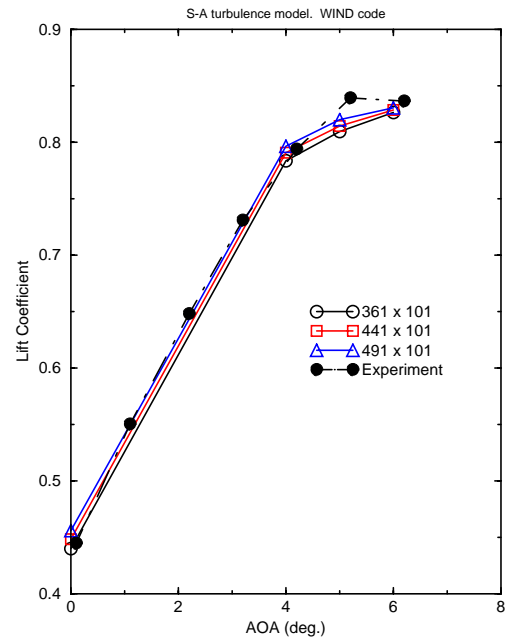


Figure 7 Circumferential direction sensitivity test  
22.5 minute 3-D ice

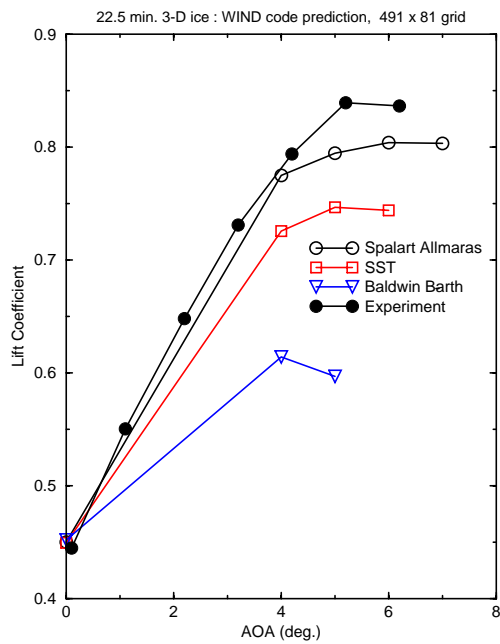


Figure 6 Effect of turbulence model on the computation

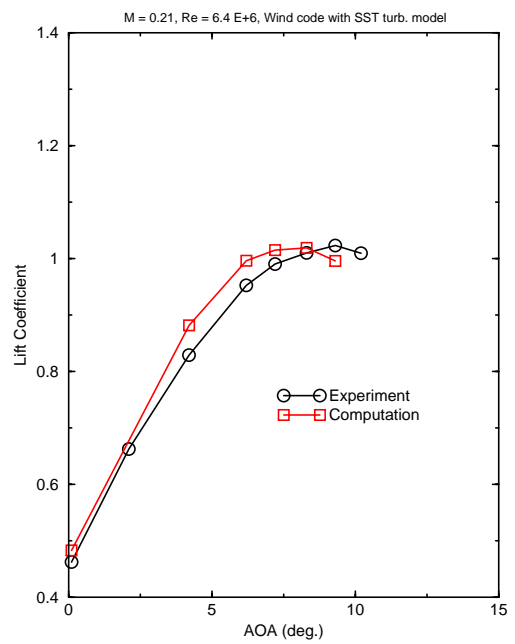


Figure 8a Lift Comparison for 6 min.3-D ice shape

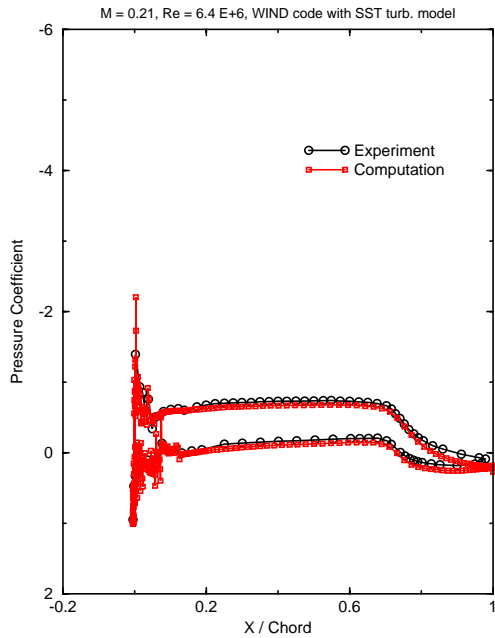


Figure 8b Comparison of Cp for 6 min. 3-D ice : AOA = 0.1 deg

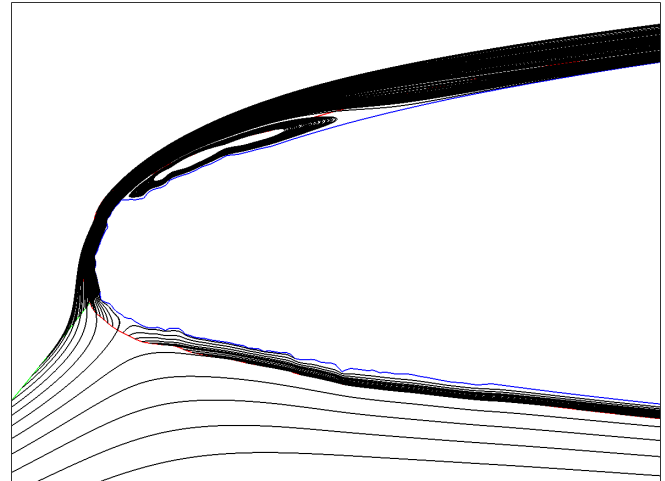


Figure 8d Flow pattern around the leading edge of the 6 minute ice at AOA = 8.3 degrees

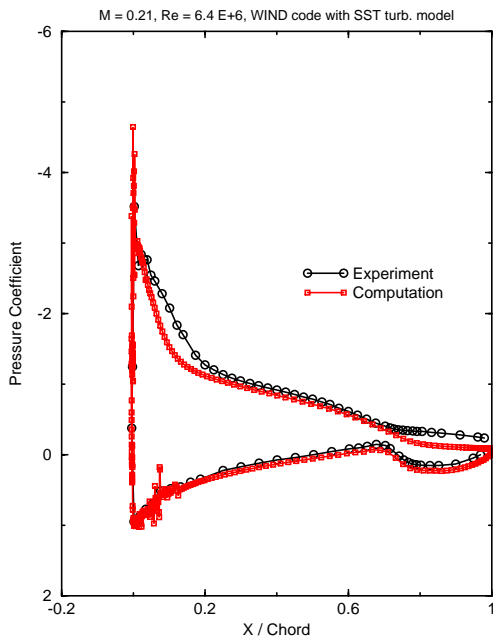


Figure 8c Comparison of Cp for 6 min. 3-D ice : AOA = 8.3 deg.

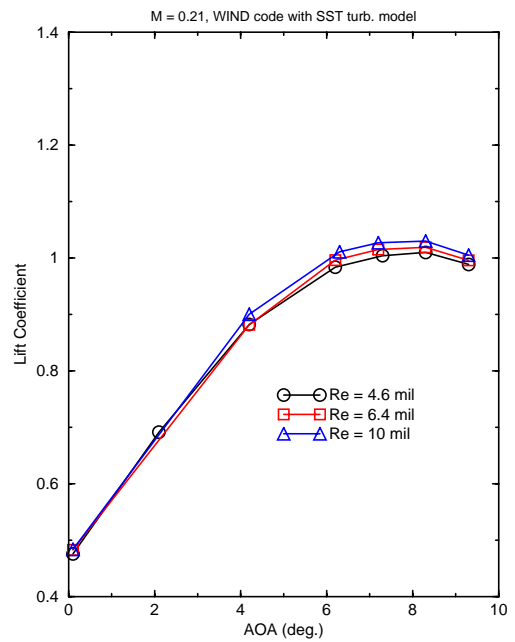


Figure 9 Reynolds number effect on the 6 min. 3-D ice

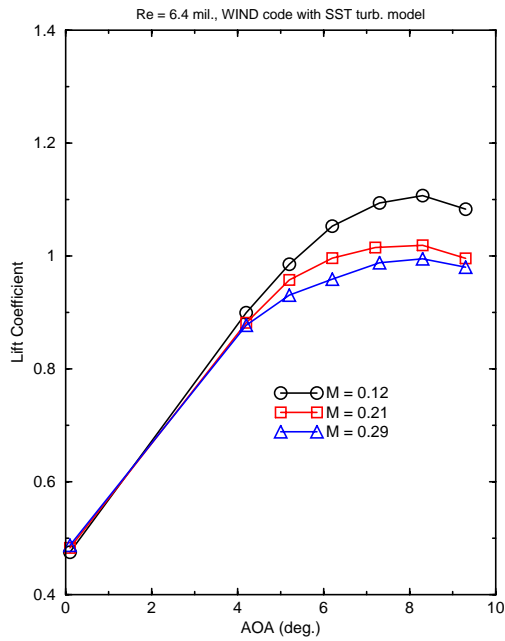


Figure 10 Mach number effect on the 6 min. 3-D ice

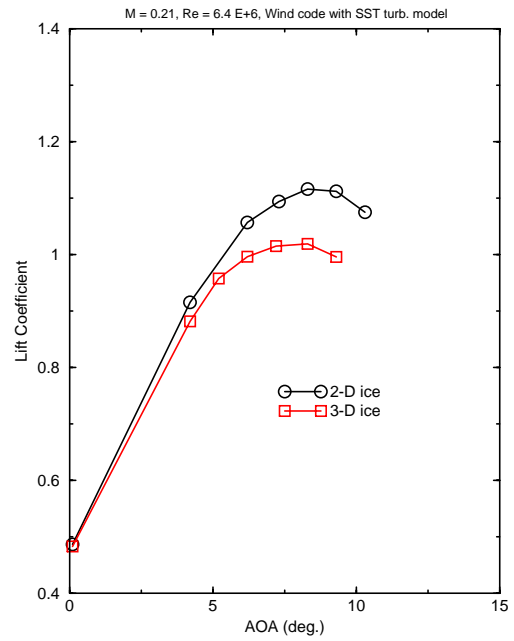


Figure 12a Lift Comparison for the 6 min. 2-D & 3-D ice

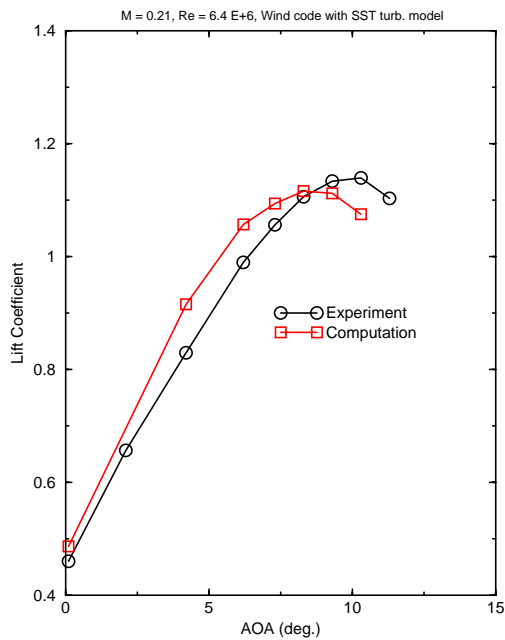


Figure 11 Lift Comparison for the 6 min. 2-D ice shape

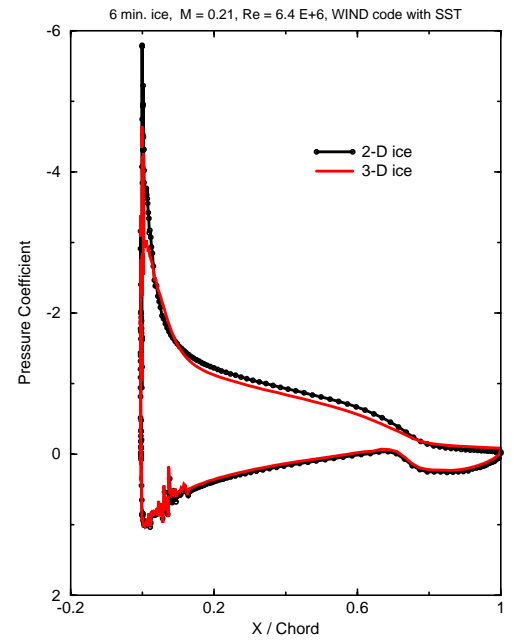


Figure 12b C<sub>p</sub> comparison for 2-D and 3-D ice : AOA = 8.3 deg.

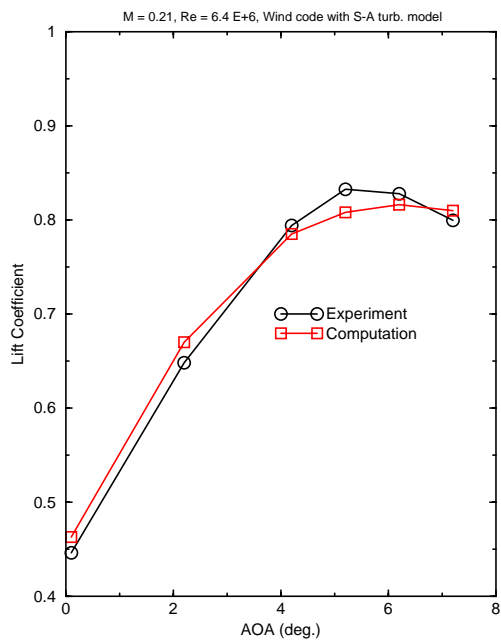


Figure 13a Lift Comparison for 22.5 min. 3-D ice shape

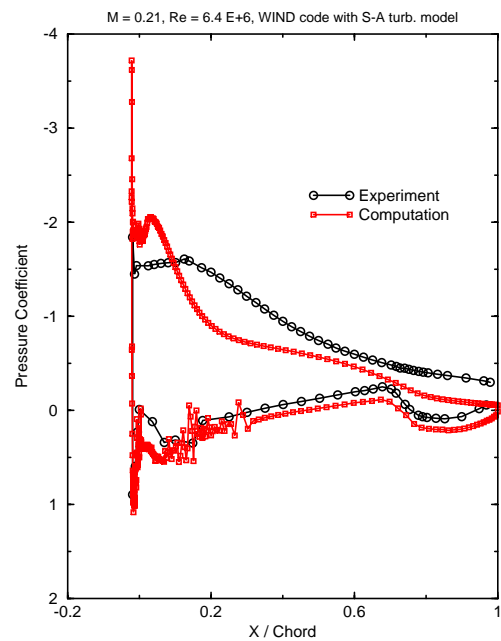


Figure 13c  $C_p$  for 22.5 min. 3-D ice : AOA = 6.2 deg.

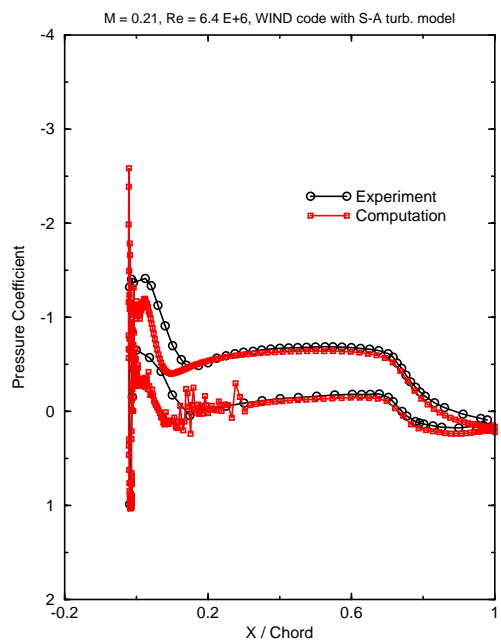


Figure 13b  $C_p$  for 22.5 min. 3-D ice : AOA = 0.1 deg.

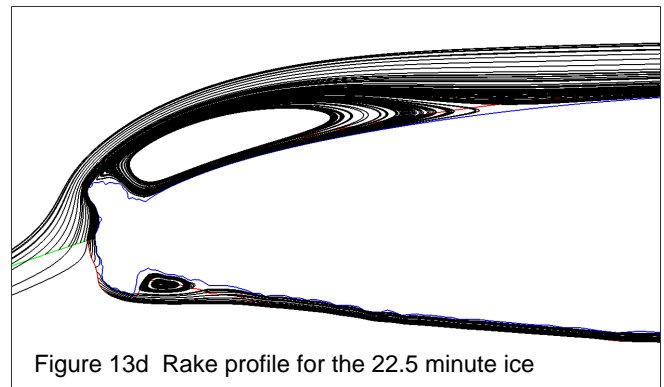


Figure 13d Rake profile for the 22.5 minute ice

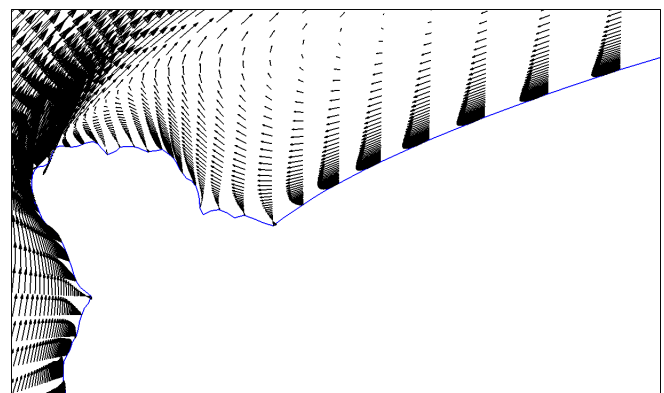


Figure 13e Velocity Profile around the leading edge horn on the upper surface of the 22.5 minute ice

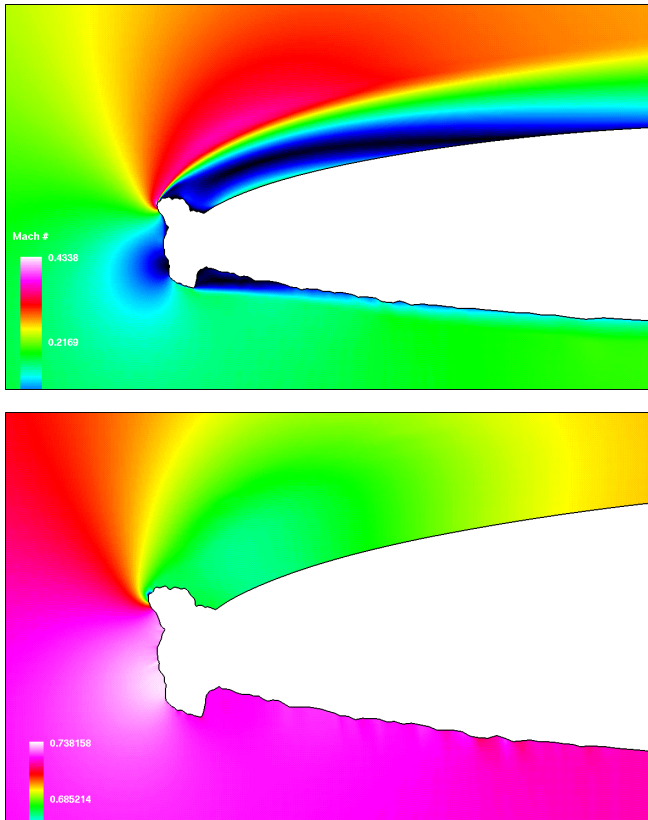


Figure 13f (top) Mach contours for the 22.5 minute ice  
Figure 13g (bottom) Pressure contours for the 22.5 min. ice

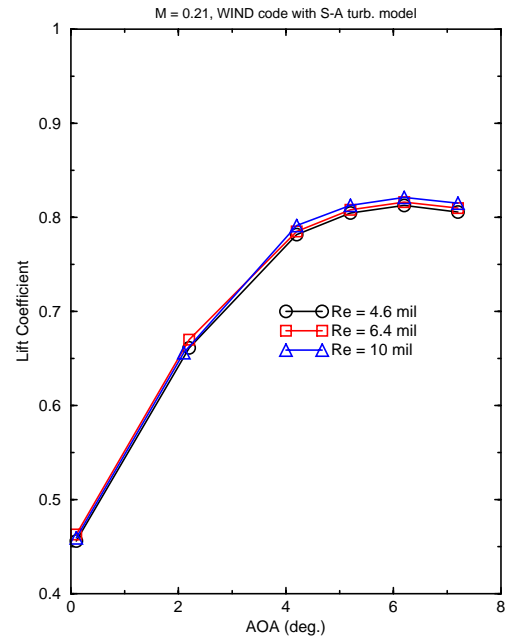


Figure 14b Reynolds number effect on the 22.5 min. 3-D ice

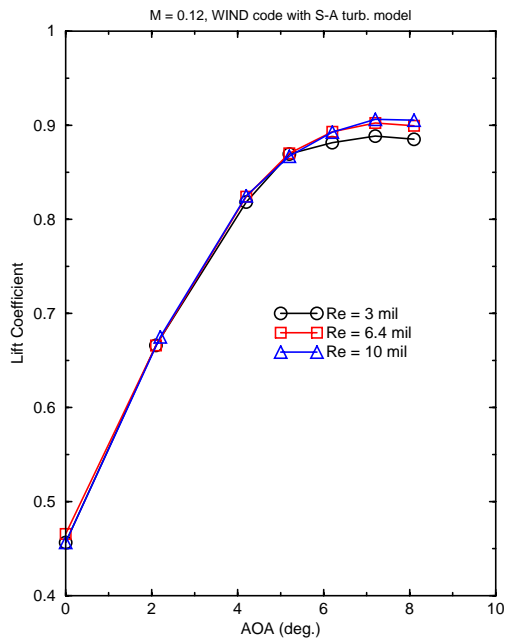


Figure 14a Reynolds number effect on the 22.5 min. 3-D ice

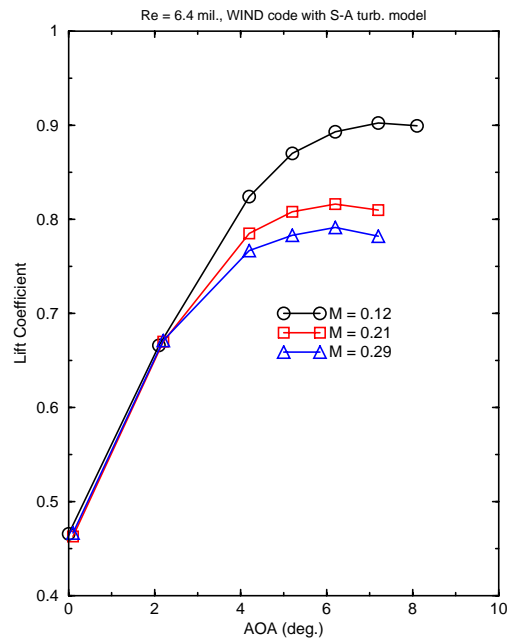


Figure 14c Mach number effect on the 22.5 min. 3-D ice

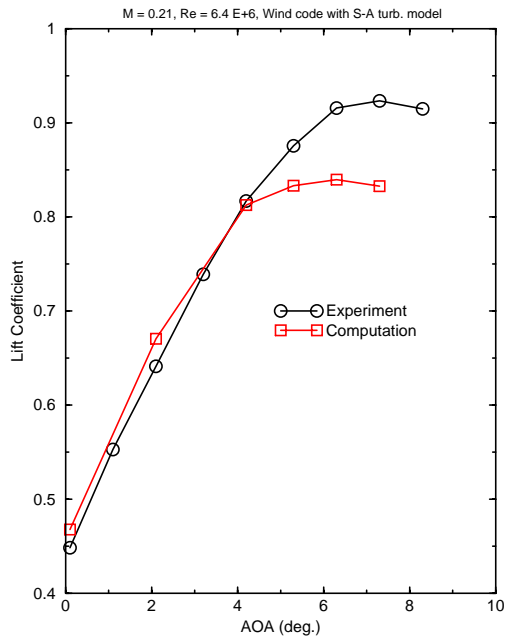


Figure 15a Lift Comparison for the 22.5 min. 2-D ice shape

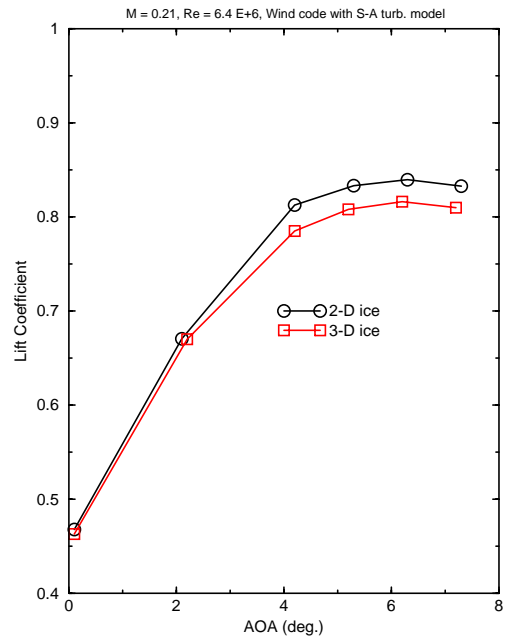


Figure 16a Lift Comparison for the 22.5 min. 2-D & 3-D ice

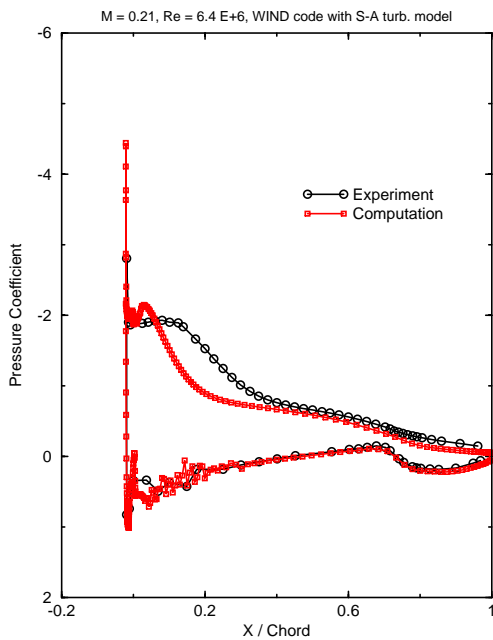


Figure 15b Cp for 22.5 min. 2-D ice : AOA = 6.3 deg.

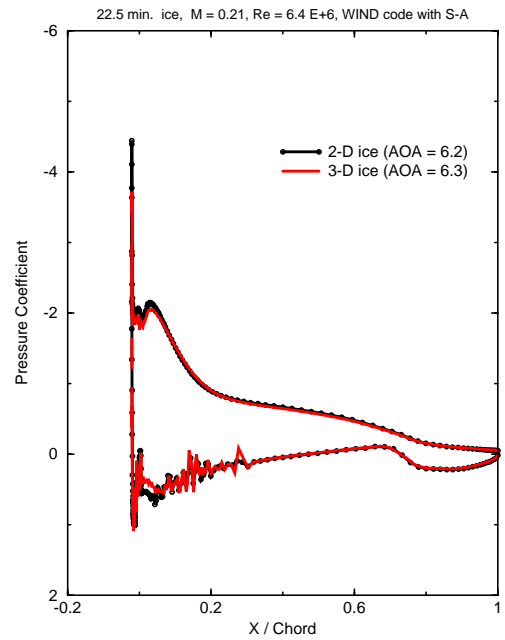


Figure 16b Cp comparison for 2-D and 3-D ice : AOA = 6 deg.



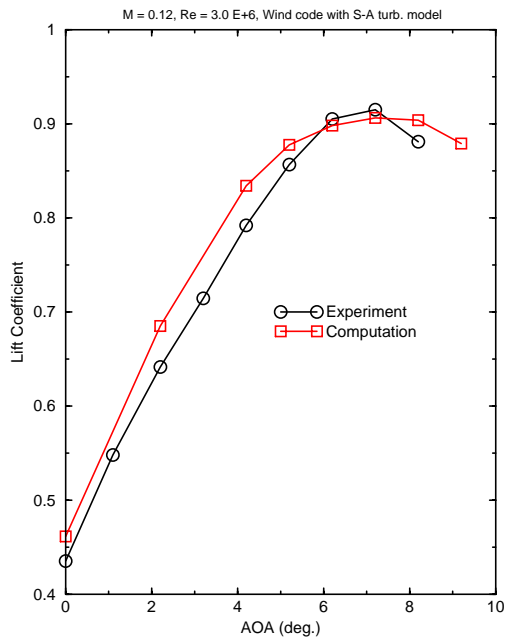


Figure 17 Lift Comparison for the 22.5 min. 2-D ice shape

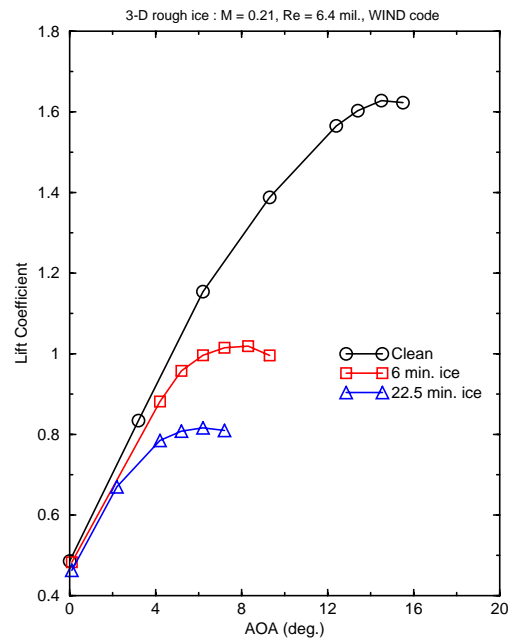


Figure 19 Effect of the 3-D ice on the lift

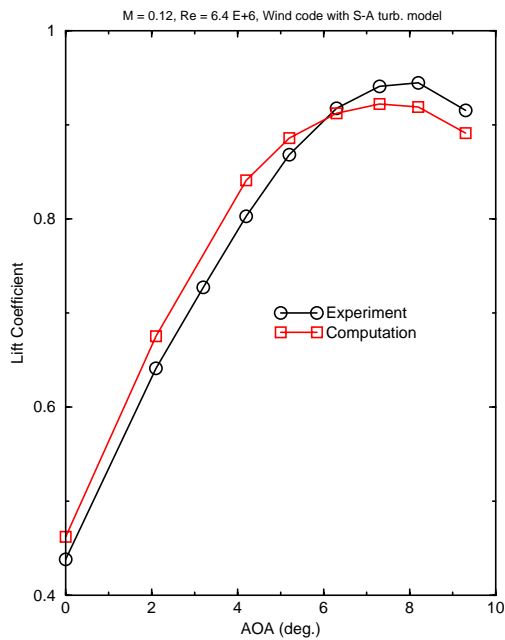


Figure 18 Lift Comparison for the 22.5 min. 2-D ice shape

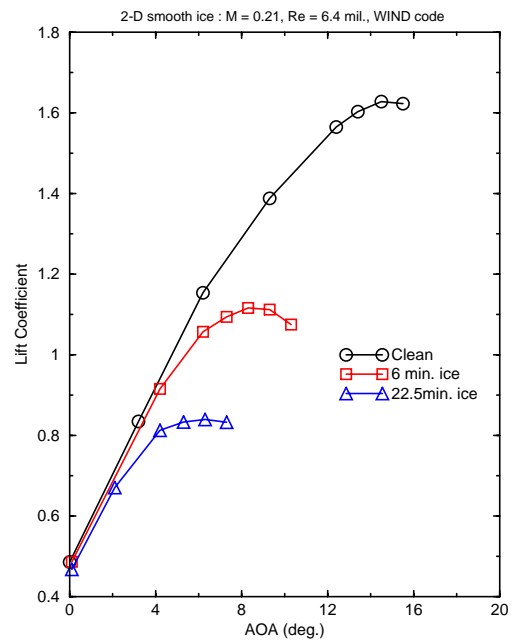


Figure 20 Effect of the 2-D ice on the lift

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13. ABSTRACT (Maximum 200 words) As a part of CFD code validation efforts within the Icing Branch of NASA Glenn Research Center, computations were performed for natural laminar flow (NLF) airfoil, NLF-0414, with 6 and 22.5 minute ice accretions. Both 3-D ice castings and 2-D machine-generated ice shapes were used in wind tunnel tests to study the effects of natural ice as well as simulated ice. They were mounted in the test section of the Low Turbulence Pressure Tunnel (LTPT) at NASA Langley that the 2-dimensionality of the flow can be maintained. Aerodynamic properties predicted by computations were compared to data obtained through the experiment by the authors at the LTPT. Computations were performed only in 2-D and in the case of 3-D ice, the digitized ice shape obtained at one spanwise location was used. The comparisons were mainly concentrated on the lift characteristics over Reynolds numbers ranging from 3 to 10 million and Mach numbers ranging from 0.12 to 0.29. WIND code computations indicated that the predicted stall angles were in agreement with experiment within one or two degrees. The maximum lift values obtained by computations were in good agreement with those of the experiment for the 6 minute ice shapes and the 22.5 minute 3-D ice, but were somewhat lower in the case of the 22.5 minute 2-D ice. In general, the Reynolds number variation did not cause much change in the lift values while the variation of Mach number showed more change in the lift. The Spalart-Allmaras (S-A) turbulence model was the best performing model for the airfoil with the 22.5 minute ice and the Shear Stress Turbulence (SST) turbulence model was the best for the airfoil with the 6 minute ice and also for the clean airfoil. The pressure distribution on the surface of the iced airfoil showed good agreement for the 6 minute ice. However, relatively poor agreement of the pressure distribution on the upper surface aft of the leading edge horn for the 22.5 minute ice suggests that improvements are needed in the grid or turbulence models.				
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